Identification of the Mechanical Joint Parameters with Model Uncertainty

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Abstract: Joint parameter identification is a key problem in the modeling of complex structures. The behavior of joint may be random due to the random properties of preload and joint geometries, contact surface and its finish, *etc*. A method is presented to simulate the joint parameters as probabilistic variables. In this method the response surface based model updating method and probabilistic approaches are employed to identify the parameters. The study implies that joint parameters of some structures have normal or nearly normal distributions, and a linear FE model with probabilistic variables could illustrate dynamic characteristics of joints.

Key words: joint parameter identification; model updating; model uncertainty; response surface

计及不确定性因素的结合面参数识别. 郭勤涛, 张令弥. 中国航空学报(英文版), 2005, 18(1): 47－52.

摘 要: 结合面参数识别是复杂结构动力学建模的关键问题。由于连接结构的接触面的大小、摩擦系数, 以及安装预应力等相关参数存在不确定性, 本文提出把连接结构的接触刚度及接触阻尼作为随机分布参数处理, 并使用基于响应面法的模型修正方法和分布代数方法进行识别, 方法可行, 便于实际工程应用。研究表明, 连接结构参数具有正态分布或近似正态分布的特点; 用线性有限元模型加上具有正态分布的接触刚度、接触阻尼模型可以描述真实结构的动态特性。

关键词: 结合面参数识别; 模型修正; 模型不确定性; 响应面法

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Finite element (FE) analysis has become a routine practice in structural dynamics. However, it is well known that a FE model can be erroneous due to mis-modeling of some parts of a structure. These parts, including mechanical joints, are often very complicated so that it may not always be possible to derive accurate models (such as a contact FE model) by using purely analytical approach. Hence, identifying or extracting a theoretical method of a mechanical joint from experimental model is an attractive and promising area which many engineers interested in[1-4].

The joint identification techniques based on combining analytical method with experimental approach can be generally divided into two main categories. The one[5-7] is to derive a series of equations which denote the relationship between joint parameters and modal parameters or FRFs (Frequency Response Functions) by solving the motion equations of the system. This kind of approach may be very sophisticated or resulting in large errors in damping identification[7].

The other one is the model updating based optimization method, whose accuracy and feasibility have made it an efficient approach in joint identification[8, 9]. However, two drawbacks should be overcome when dealing with joint identification. First, model updating is efficient when the parameters have little error. But joint parameters may have large errors (> 50%) need to be updated. Secondly, FE models need model reduction when comparing with experimental models.

In structural dynamics, the FE model of a mechanical joint includes springs, damper and other element formulations. Further more, the model can be nonlinear or has stochastic features. Model-

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ing of joint in structural dynamics has been studied extensively. Ganggaharan[10] presents a probabilistic system identification method by using static response. Howard Walther[11] studied on model uncertainty and experimental data variability of a bolted joint. Qiao[12] developed a relaxation model of joint with the consideration of time-independent uncertainty. Aumann[13] proposed a method to illustrate a bolted joint by a Smallwood model.

The behavior of joint may be random due to the random properties of preload and joint geometries, contact surface and its finishes, *etc*. Assuming that the normal and tangential stiffnesses and the corresponding damping coefficients can illustrate the characteristics of the joint, it can be concluded that the stiffnesses and their damping coefficients are random and variable. That is the very reason why the modal parameters of structures with joints are random. In EMA (Experimental Modal Analysis), modal damping ratios have more variance than frequencies, and this is not only due to the test noise but also due to the changing of damping itself.

In order to model those structures with joint model uncertainty, both mean values and variance are needed in FEA response prediction. This also can meet the needs of VPES (Virtual Prototyping Experiment Simulation), FE model validation and structural reliability engineering.

The study presents here is a RSM (Response Surface Methodology) based model updating technique[14] combined with probabilistic approach[15]. Firstly, using EMA to obtain the stochastic properties of the modal parameters. Secondly, identifying the mean values of the joint parameters by the model updating technique. The third step is estimation of the standard deviations of the parameters by using the probabilistic approach.

1 Basic Theory

In this study it is presumed that both joint parameters and response features (such as modal frequencies and damping ratios) are random variables with normal or nearly normal distributions. A framework of joint identification is shown in Fig. 1. In this part, three issues involved in the joint identification with uncertainty will be discussed.

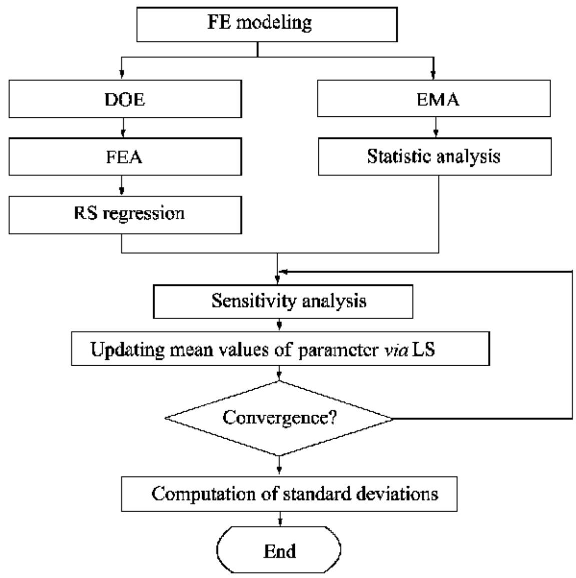


Fig. 1 The flow chart of parameters identification of the mechanical joint with model uncertainty

1.1 FE modeling of mechanical joint

For a structure in free vibration mode, the mass matrix, stiffness matrix and damping matrix of the FE model denote as $\boldsymbol{M}$, $\boldsymbol{K}$ and $\boldsymbol{C}$. Suppose the damping of system is viscous, then, $\boldsymbol{C} = \beta_1 \boldsymbol{M} + \beta_2 \boldsymbol{K}$, where β_1 and β_2 can be determined by the lower order modal damping ratios. For those structures whose damping can not expressed as the linear combination of $\boldsymbol{M}$ and $\boldsymbol{K}$, a more complicated model should be introduced[16].

Considering the model of a joint, the FE model should be supplemented with joint stiffness $\boldsymbol{K}_\Delta$, joint damping matrix $\boldsymbol{C}_\Delta$ and joint mass matrix $\boldsymbol{M}_\Delta$. By solving the eigenvalue problem, modal parameters(Φ, Λ) are obtained. Suppose the damping is viscous, then the following equations exist:

$$\boldsymbol{C}_\mathrm{r} = \Phi^\mathrm{T}[\boldsymbol{C} + \boldsymbol{C}_\Delta]\Phi, \quad \boldsymbol{M}_\mathrm{r} = \Phi^\mathrm{T}[\boldsymbol{M} + \boldsymbol{M}_\Delta]\Phi,$$

$$\boldsymbol{K}_\mathrm{r} = \Phi^\mathrm{T}[\boldsymbol{K} + \boldsymbol{K}_\Delta]\Phi, \quad \xi_\mathrm{r} = \boldsymbol{C}_\mathrm{r}/2\sqrt{\boldsymbol{M}_\mathrm{r}\boldsymbol{K}_\mathrm{r}}$$

where ξ_r denotes the modal damping ratio of the assembly.

1.2 Identification of mean values of joint parameters via RSM based model updating

The method includes the following main

steps: Compute response features of every design point in the space spanned by the parameters according to DOEs (Design of Experiments). Then a high order polynomial model (or other RS models such as an artificial neural net work) is regressed as: $y_j(p) = f_j(p) + \varepsilon_j$. Then the updating problem can be expressed as a optimization procedure

$$\min_p \| R(p) \|_2^2,\ R(p) = \{y_E\} - \{y_A(p)\}$$
$$\text{s.t} \quad p_l \leqslant p \leqslant p_u \tag{1}$$

where $f_j(p)$ is the RS models; ε_j is the bias error of regression; p is the vector of joint parameters, $\{y_E\}$ and $\{y_A\}$ are the mean values of experimental and analytical response features, respectively; R is the residue; p_l and p_u are the lower and upper bound of p. Obviously, both R and $\{y_A\}$ are the functions of p. The optimization problem can be solved by the following equation

$$\Delta p = S^+ \Delta y \tag{2}$$

where S^+ is the pseudo inverse of the sensitivity matrix[14] (or known as Jacobian matrix). The sensitivity matrix can be derived from the RS models by differentiation.

1.3 Estimation of the standard deviations of joint parameters

The equation to compute standard deviations of response features is[15]

$$\sigma_y^2 = \sum_{i=1}^{n} (\partial y / \partial p_i)^2 \sigma_{p_i}^2 \tag{3}$$

where σ_y^2 and $\sigma_{p_i}^2$ are the standard deviations of response features and joint parameters, respectively. and $\partial y / \partial p_i$ is the first order deviation of y versus p. Suppose the number of response features is m, then Eq. (3) can be rewritten as

$$\sigma_{y_j}^2 = \sum_{i=1}^{n} (\partial y_j / \partial p_i)^2 \sigma_{p_i}^2 \qquad (j = 1, \cdots, m) \tag{4}$$

In matrix formula Eq. (3) is

$$\{\sigma_{y_j}^2\} = \boldsymbol{Z} \{\sigma_{p_i}^2\} \tag{5}$$

where

$$\boldsymbol{Z} = \begin{bmatrix} (\partial y_1/\partial p_1)^2 & (\partial y_1/\partial p_2)^2 & \cdots (\partial y_1/\partial p_n)^2 \\ (\partial y_2/\partial p_1)^2 & (\partial y_2/\partial p_2)^2 & \cdots (\partial y_2/\partial p_n)^2 \\ \vdots & \vdots & \vdots \quad \vdots \\ (\partial y_m/\partial p_n)^2 & (\partial y_m/\partial p_n)^2 & \cdots (\partial y_m/\partial p_n)^2 \end{bmatrix}$$

Then standard deviations of joint parameters are

$$\{\sigma_{p_i}^2\} = \boldsymbol{Z}^+ \{\sigma_{y_j}^2\} \tag{6}$$

The pseudo inverse of $\boldsymbol{Z}$ can be solved by singular value decomposition.

2 Experimental Case Study

Two questions will be answered in this case study. The first is whether the joint parameters and the response features of structures in practical have normal distributions or not. The second is whether the linear FE model combined with probabilistic joint parameters can illustrate the dynamic properties of a structure or not.

2.1 Modeling of the flange joint structure

Since bolted joint and welded joint as well as rivets are very common in aero and space structures, a flange bolted joint structure (shown in Fig. 2) is employed in the case study. A box section tube with a square plate at its end as flange is connected to another fixed plate by using four bolts

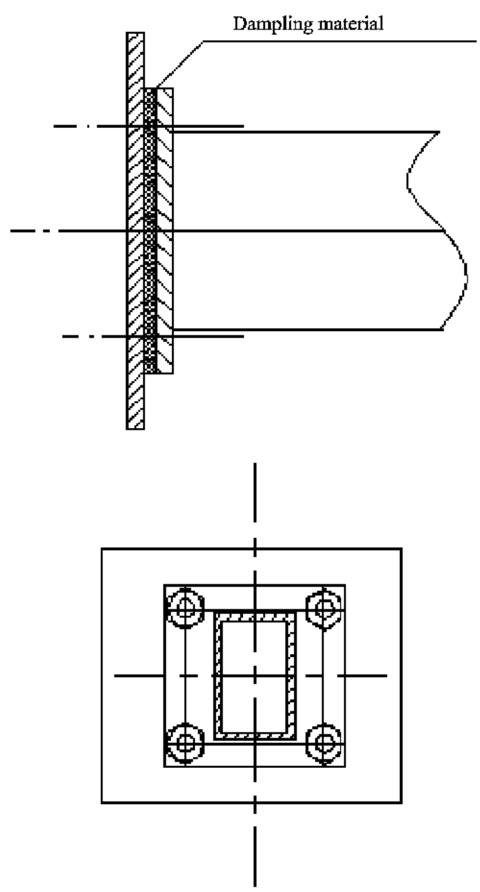


Fig. 2 The flange joint structure

with 3mm thickness damping material between them.

The FE model of the structure and joint position are shown in Fig. 3. The FE model consists of

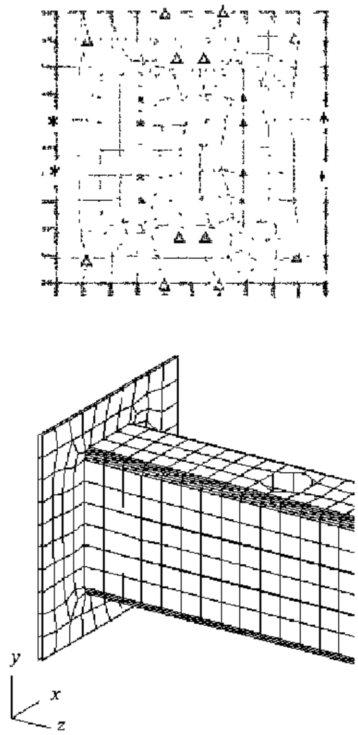


Fig. 3　The FE model of flange joint structure

4000 shell elements and 48(3DOF) spring elements along with 48(3DOF) dampers in △ and * positions. △ and * stand for different z-direction stiffness and damper. Hence, there are 6 joint parameters need to be identified. Response features are the lower five order modal frequencies and damping ratios.

2.2　EMA and identified results

A sequence of experiments is designed in order to examine the modal parameters of the structure. During the test, excitations are generated by using a hammer with a force transducer, and all impacts are applied at the center of the structure and at approximately the same level. Motions are measured by using a accelerometer mounted with glue at the free end. The excitation force and motion response are captured by using a HP35670 signal analyzer. The signals are analyzed in N-Modal software.

Eight experiments are designed to assess randomness in assembly/disassembly. The variance due to the test itself is examined by comparing several results of the same assembly (error of frequency < 0.1%, damping ratio < 1%). After statistic analysis of the data, the means and the standard derivations of the response features are obtained. From the normal probability plot it can be concluded that data distribution are normal or nearly normal (shown in Fig. 4 and Fig. 5).

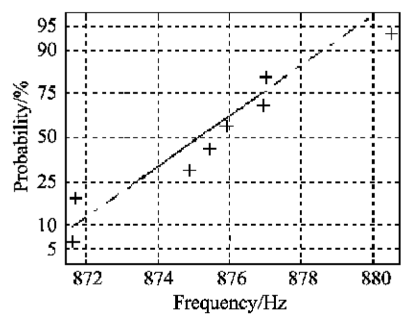


Fig. 4　Normal probability plot of the modal frequency

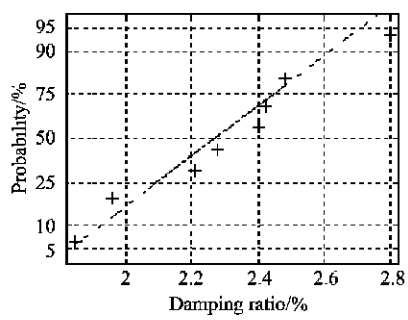


Fig. 5　Normal probability plot of the modal damping ratio

In the example, D-optimal design with 25 runs is employed in regression of the five order polynomials. Then the mean values and standard deviations of the joint parameters are obtained using the presented approach.

In order to verify whether the identified parameters consist with the test, the mean values and standard deviations of modal frequencies and damping ratios are computed by FEA combined with Monte Carlo simulations by using the identified parameters. By comparing the normal PDF plots of the identified result with test, it is obviously true that the distributions of modal frequencies match each other quite well, and modal damping ratios match almost well (shown in Fig. 6 and Fig. 7).

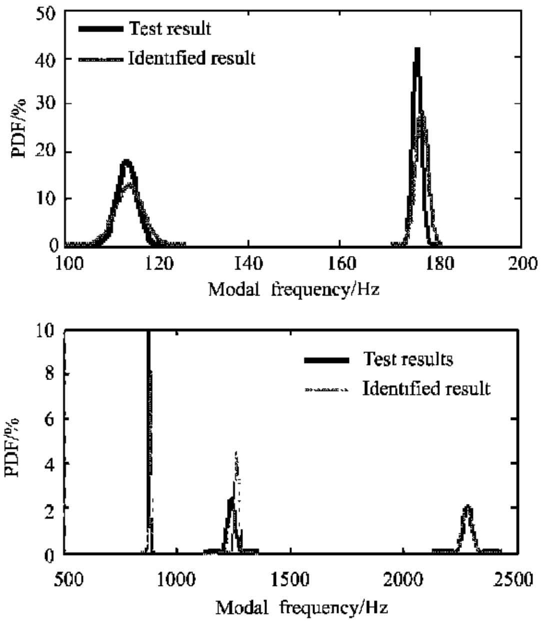
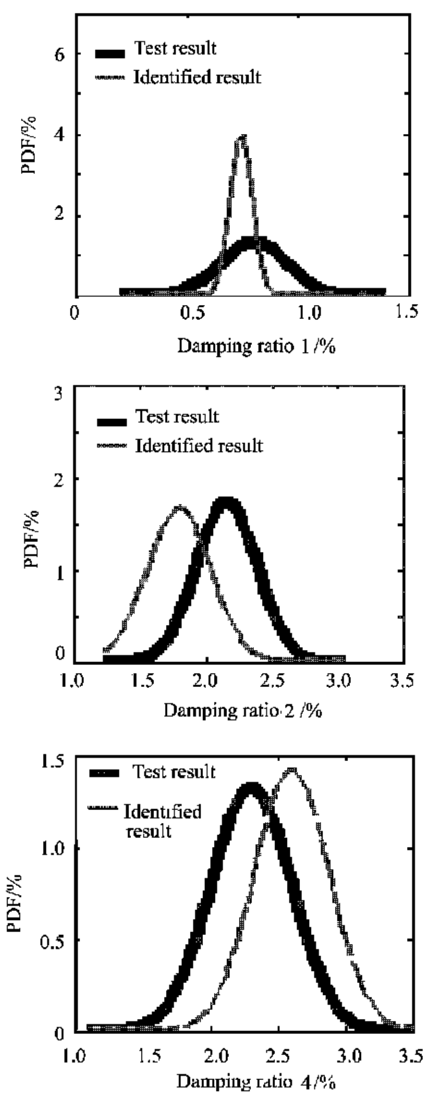


Fig. 6 Normal PDF plots of both the experimental and identified FE model modal frequency



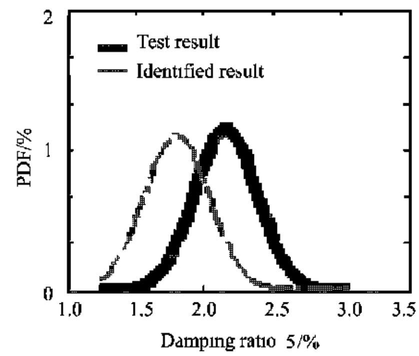


Fig. 7 Normal PDF plots of both the experimental and identified FE model modal damping ratios

3 Conclusions

The experimental study implies that the presented joint identification approach is valid in dealing with joints with uncertainty. The linear FE model combined with random joint parameters with normal distributions can illustrate the dynamic characteristics of a structure more reasonably. Theoretically, the presented method can be used in complex modal area or nonlinear dynamics, the only difference is that the direct FEA will be more sophisticated. How to model a joint more realistically and feasibility is a key problem and needs further study. The accuracy of standard deviations can be improved by taking account high order Taylor series in probabilistic approach.

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